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Technique for Measuring the Spin Rate of Kinetic Energy Projectiles

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Kinetic energy projectiles were fitted with dihedral plugs in their tracer wells in an attempt to measure their spin histories via Doppler radar. Data from three projectiles were reduced and the approximate steady-state spin rates were obtained.

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1. INTRODUCTION

Knowing the spin history of a kinetic energy (KE) projectile is essential in designing this type of ammunition since spin frequencies that are close to the projectile's structural frequencies, or its yaw frequency, could be catastrophic.

Obtaining spin data for this type of projectile is not a trivial task. Yaw cards may be used to measure the spin rate (Pennekamp 1990), but this technique is very expensive, is labor intensive, and can yield misleading results if the projectile spin is unusual. High-speed motion pictures may also be utilized to measure the spin rate, but only a fraction of the flight will be recorded. Radar data have been used to measure the spin of artillery projectiles, but the small radar cross section and the slow spin rates of the KE rounds may prevent such analysis.

This report describes the use of a notched plug located in the tracer-well of the projectile as an aid for measuring the spin history of KE rounds via Doppler radar. The initial results are promising, but further refinements must be made.

2. BACKGROUND

2.1 Laboratory Experiments With the Tracer-Well Plug. A series of experiments conducted at the U.S. Army Ballistic Research Laboratory (BRL) revealed that a 90° dihedral plug manufactured to fit into the tracer-well of KE rounds would induce an amplitude modulation (AM) of the reflected radar signal when the plug/fin assembly was rotated (Bossoli, unpublished data). The reflective surface of the plug must have dimensions on the order of the wavelength of the transmitted radar signal. The plug designed for typical Doppler radars used in projectile testing is pictured in Figure 1.

The laboratory tests involved mounting the plug (Figure 1) into the tracer-well of a fin assembly for a KE projectile. The fin assembly was then mounted on a stand and rotated about its axis of symmetry to discrete angular positions. At each position, the plug/fin set was illuminated by continuous wave, linearly polarized radiation over a range of frequencies

common to tracking radars. The power of the reflected radiation for each frequency and orientation was then measured.

The experiments showed that the amplitude of the reflected signal varied with the angular orientation of the plug as well as with the frequency of the impinging radiation. Figure 2 shows the maximum difference, or anisotropy, in reflected signal power due to roll orientation for a specific frequency range. The radar available for the field test operated in the x-band (8–12 Ghz) frequency range. The anisotropy is expressed in dB* which is a measure of power relative to a reference power. In the frequency band that was studied, the lowest degree of anisotropy was approximately 5 dB, which means that at that frequency, the reflected signal power fluctuated by about a factor of three as the assembly was rotated. A 90° dihedral corner reflector will only exhibit orientational anisotropy with respect to radar polarization if its dimensions are less than several wavelengths long, otherwise the dihedral's radar cross section (RCS) is considered to be in its optical regime and this anisotropy will not be seen (Skolnik 1990). The diameter of the dihedral plug that was tested is approximately equal to one wavelength of x-band radiation (25 mm–37.5 mm) and, therefore, does not put its RCS in the optical regime. In the nonoptical regime, the area of the reflecting surface which is aligned with the linearly polarized E-field of the impinging radiation greatly affects its RCS. When the E-field is parallel to the dihedral axis (as shown in Figure 1), the reflective surfaces offer the most area and therefore the largest RCS. At other orientations, the dihedral RCS will be less with the minimum occurring when the dihedral axis and the E-field are perpendicular. This changing area and the fact that the dihedral's dimensions put its RCS in the nonoptical regime for x-band radiation give rise to the measured orientational anisotropy presented in Figure 2. The RCS of the dihedral plug, as seen by a linearly polarized x-band radar, will, therefore, have a rotational dependence of the form,

$$\mathrm{RCS} \propto A|\cos\theta| + \mathrm{Constant}$$

or

$$\mathrm{RCS} \propto A|\cos 2\pi f t| + \mathrm{Constant}$$

* dB = $10\mathrm{LOG}_{10}$ (Reference Power/Measured Power)

where A is the maximum amplitude, θ is the angular difference between the dihedral axis and the E-field, f is the dihedral plug roll rate, and t is time.

2.2 Field Testing With the Tracer-Well Plug. In order to test the concept of using a tracer-well plug and a radar to measure spin rates, it was decided to install plugs on KE projectiles tested at a firing range of the Combat Systems Test Activity (CSTA), Aberdeen Proving Ground (APG), in July of 1991.

This test utilized an x-band Doppler radar to provide velocity data. The radar was of the continuous wave, linearly polarized variety. A number of rounds were fitted with the tracer-well plug in order to see if the Doppler return signal would be amplitude modulated by the projectile spin. The Doppler return signal from the radar was recorded with an analog tape recorder for later analysis.

It should be noted that this test is slightly different than the laboratory experiments in that the Doppler return signal was being monitored instead of the reflected signal since it was readily available from the radar. The Doppler return signal is the difference in frequency of the transmitted signal and the reflected signal. The Doppler return signal is produced by circuits internal to the radar and has a much lower frequency than the reflected signal. Equipment to monitor the reflected signal in the field could not be obtained in a timely and cost effective manner. However, it was hoped that any AM produced upon the reflected signal by the plug would carry through onto the Doppler return signal.

3. FIELD TEST RESULTS

The data were examined for an AM response, but no realistic data were found. The automatic gain control (AGC) circuits of the radar had masked this modulation. However, frequency modulation (FM) was found in the Doppler return signal. The source of this FM has been theorized to be the result of the measurement of the velocity due to rotation of the plug. Calculations based on plug geometry showed that the velocities of certain points on the plug are consistent with velocities measured from the ripples of the discriminator output. A description of this theory follows.

Initially, when the radar radiation hits the surface of the plug, its frequency is shifted by an amount, f_{d1}, due to the projectile velocity, V_d. This shift in frequency is commonly called the *Doppler shift frequency* or the *Doppler shift*. The value of f_{d1} can be expressed as:

$$f_{d1} = |V_d|/\lambda$$

where f_{d1} is the Doppler shift frequency due to projectile velocity, $|V_d|$ is the magnitude of the projectile velocity in the direction of the radar radiation propagation, and λ is the original wavelength of the radar radiation. The radiation is then reflected and propagates toward the other surface of the plug.

When the radiation hits this surface, its frequency is Doppler shifted again due to the tangential velocity, V_r, of the rotating plug. The component of V_r in the radiation propagation direction actually causes this Doppler shift, but since the magnitude of this component is equal to that of V_r at certain locations, which provide maximum Doppler shift, it can be said that V_r is the velocity that causes the Doppler shift to simplify this explanation.

Radiation hits all points on the surface of the plug. With that in mind, one must wonder which magnitude of V_r is being measured since V_r is not constant for all points on the plug. At a constant spin rate, the tangential velocities of the points on the plug will vary with their distance from the plug center line (Figure 3a). This distance can be expressed as a function of depth into the plug. The points on the plug at shallow depths posses more tangential velocity and therefore larger Doppler shift than those at the deeper depths. Larger Doppler shifts are resolved better by the radar.

The surface area across the plug is also a function of depth. This area increases with depth (Figure 3b). The Doppler shifts created by the velocities of the points in the regions of larger surface area are more readily detected than those in regions of less surface area since more radiation is reflected back to the radar. The amount of radiation reflected back is directly proportional to the power of the signal that the radar receives. The radar will resolve the signals with higher power levels.

There is a depth where the combination of these properties are optimized. This depth can be determined by finding the maximum of the product of V_r and the surface area across the plug as functions of depth. Figure 4 shows a plot of this product vs. depth. The depth at which these properties are optimized was calculated to be approximately 29% into the plug. With this, $|V_r|$ can be expressed as:

$$|V_r| = 2\pi(.71D)f_s$$

or

$$|V_r| = 1.36\pi Df_s,$$

where $|V_r|$ is the magnitude of the effective tangential velocity of the points on the plug's surface due to plug rotation, D is the maximum depth of the plug, and f_s is the projectile spin frequency. The Doppler shift caused by the tangential velocity of the plug can, therefore, be expressed as:

$$f_{d2} = |V_r|/\lambda$$

or

$$f_{d2} = 1.36\pi Df_s/\lambda.$$

The radiation is reflected again so that it propagates in a direction opposite to that which it was transmitted (i.e., it propagates toward the radar). When the radiation reaches the radar receiver, its frequency is shifted again due to the apparent velocity of the radar moving away from the projectile (an observer on the projectile would see the radar traveling with velocity V_d). This Doppler shift frequency can be expressed as:

$$f_{d3} = |V_d|/\lambda$$

where f_{d3} is the Doppler shift frequency due to projectile velocity (or apparent radar velocity), $|V_d|$ is the magnitude of the projectile velocity (or apparent radar velocity) in the direction of the radar radiation propagation, and λ is the original wavelength of the radar radiation.

The total Doppler shift frequency that is measured by the radar is the sum of the three previously described Doppler shifts. Algebraically stated,

$$f_{d\ total} = f_{d1} + f_{d2} + f_{d3}$$

since $f_{d1} = f_{d3}$, and $f_{d2} = 1.36\pi Df_s/\lambda$, it can be written:

$$f_{d\ total} = 2f_{d1} + 1.36\pi Df_s/\lambda$$

or

$$f_{d\ total} = (2|V_d| + 1.36\pi Df_s)/\lambda.$$

The linearly polarized radiation transmitted from the radar will only achieve optimum reflections across the plug when the plug is aligned with the radiation's E-field as described in Section 2.1. This alignment occurs twice per spin cycle due to the plug symmetry. Misalignment of the plug and the radiation's E field attenuate the effect that f_{d2} has on $f_{d\ total}$. Because of this, an attenuation factor must be included in the $f_{d\ total}$ equation. This factor is:

$$\alpha = |\cos 2\pi f_s t|$$

where α is the misalignment attenuation factor, f_s is the projectile spin frequency, and t is time. This attenuation factor only affects the f_{d2} term in the $f_{d\ total}$ equation. Looking at only the time varying f_{d2} term, we see that

$$f_{d2}(t) = 1.36\pi Df_s|\cos 2\pi f_s t|/\lambda$$

or

$$f_{d2}(t) = A|\cos 2\pi f_s t|$$

and

$$f_{d\ total}(t) = 2|Vd| + A|\cos 2\pi f_s t|$$

which signifies that a modulated Doppler shift in addition to the Doppler shift due to projectile velocity should be produced with the plug installed. Figure 5 shows a typical propagation path of the radar radiation during its interaction with the plug.

The Doppler data were input to a standard telemetry frequency discriminator that converts input frequency to a DC output voltage. If properly calibrated, the discriminator will produce the velocity history of a projectile when the Doppler data are input. The discriminator output for a round not fitted with the plug is pictured in Figure 6. The trace shows system noise and the projectile velocity history, which is apparent from the downward slope, but no FM is apparent. Recall that the discriminator output is proportional to the frequency that is input. Therefore, a change in input frequency corresponds to a change in the amplitude of the output voltage.

Figure 7 shows the discriminator output for a round that was fitted with the tracer-well plug. This trace too has a downward slope indicating the projectile velocity history, but in addition, it has a periodic signal superimposed on it.

A band-pass filter was applied to the discriminator output in order to remove the high-frequency noise and the downward slope due to the decreasing projectile velocity. Figure 8 shows the filtered discriminator data.

The filtered data were then digitized, and zero crossings were detected via a computer program. The projectile spin rate was then calculated by dividing the zero crossing frequency data by a factor of two. The division by two is necessary since the plug visits its most reflective orientation twice per revolution.

The spin frequency vs. time plots for three KE rounds that were fitted with the tracer-well plug can be seen in Figures 9–11. These plots represent realistic spin histories for the projectiles that were tested (Brandon, private communication). The data points designated by the plus symbol were obtained by measuring the projectile fin signatures from yaw cards.*

A block diagram of the equipment used to obtain the spin history from the Doppler radar and the flow of the data is shown in Figure 12.

4. CONCLUDING REMARKS

This first attempt in developing a technique for measuring the spin history of KE rounds has exposed areas of improvement that could make future efforts more accurate and less tedious.

It is apparent from the scatter of the spin frequency estimates vs. time that more work must be done in building a better zero crossing detector program and/or digitizing the filtered data at a higher sampling rate to obtain better resolution.

The AM caused by the plug rotation may be preserved by eavesdropping on the reflected radar signal. An independent antenna and receiver can be used to detect the reflected signal directly rather than the Doppler return signal. Ideally, the only AM in the reflected signal would be caused by the plug.

Tests with a radar of a higher transmitter frequency will take place in the future. This radar may eliminate the need for the tracer-well plug altogether by looking at the modulation produced by the projectile fins themselves and, therefore, allowing the measurement of spin rate without disturbing the projectile hardware.

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* Mr. Richard A. Pennekamp, of BRL, obtained this data.

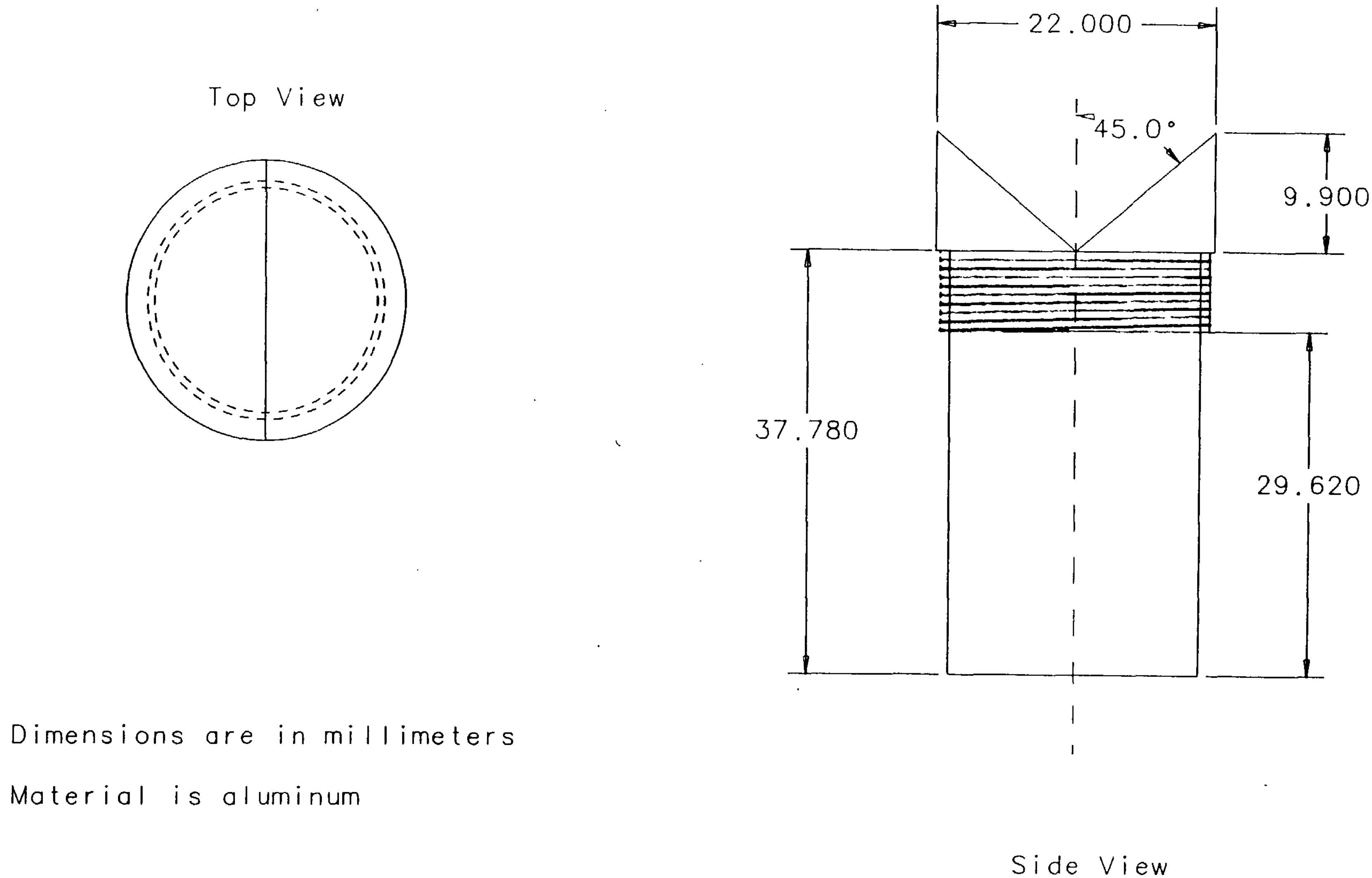


Figure 1. Tracer-Well Plug for KE Projectile.

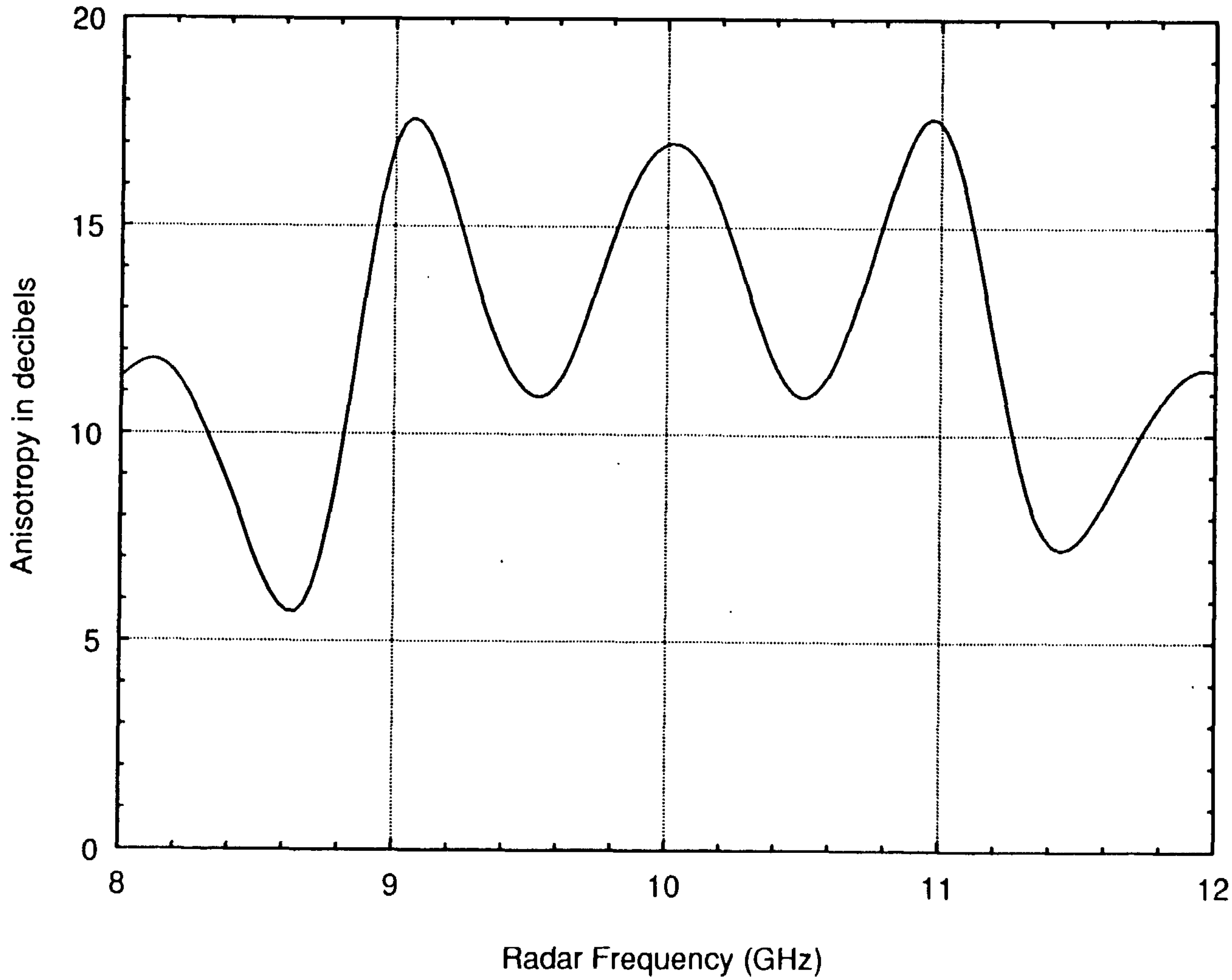
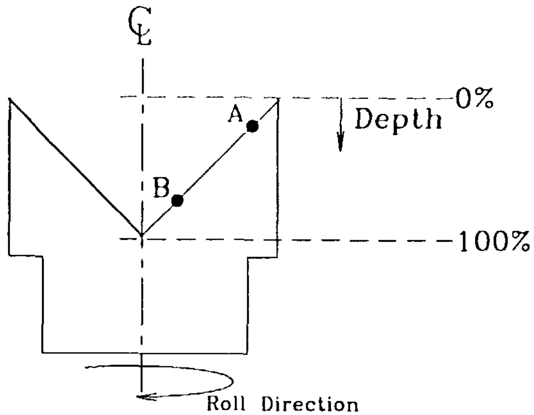
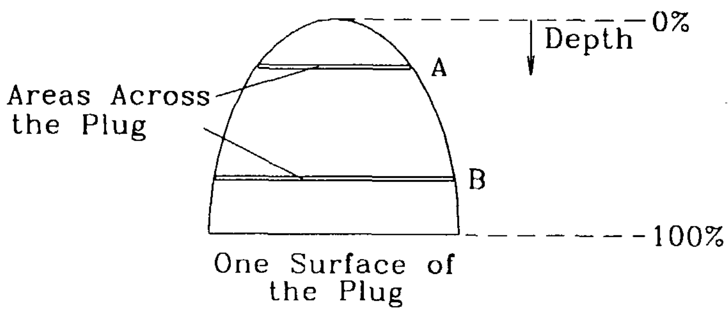


Figure 2. Anisotropy vs. Frequency for the Tracer-Well Plug.



The tangential velocity at point A is greater than that at point B.

Figure 3a. Variation of Tangential Velocity With Depth.



The area across the plug at A is less than that at B.

Figure 3b. Variation of Area Across the Surface of the Tracer-Well Plug With Depth.

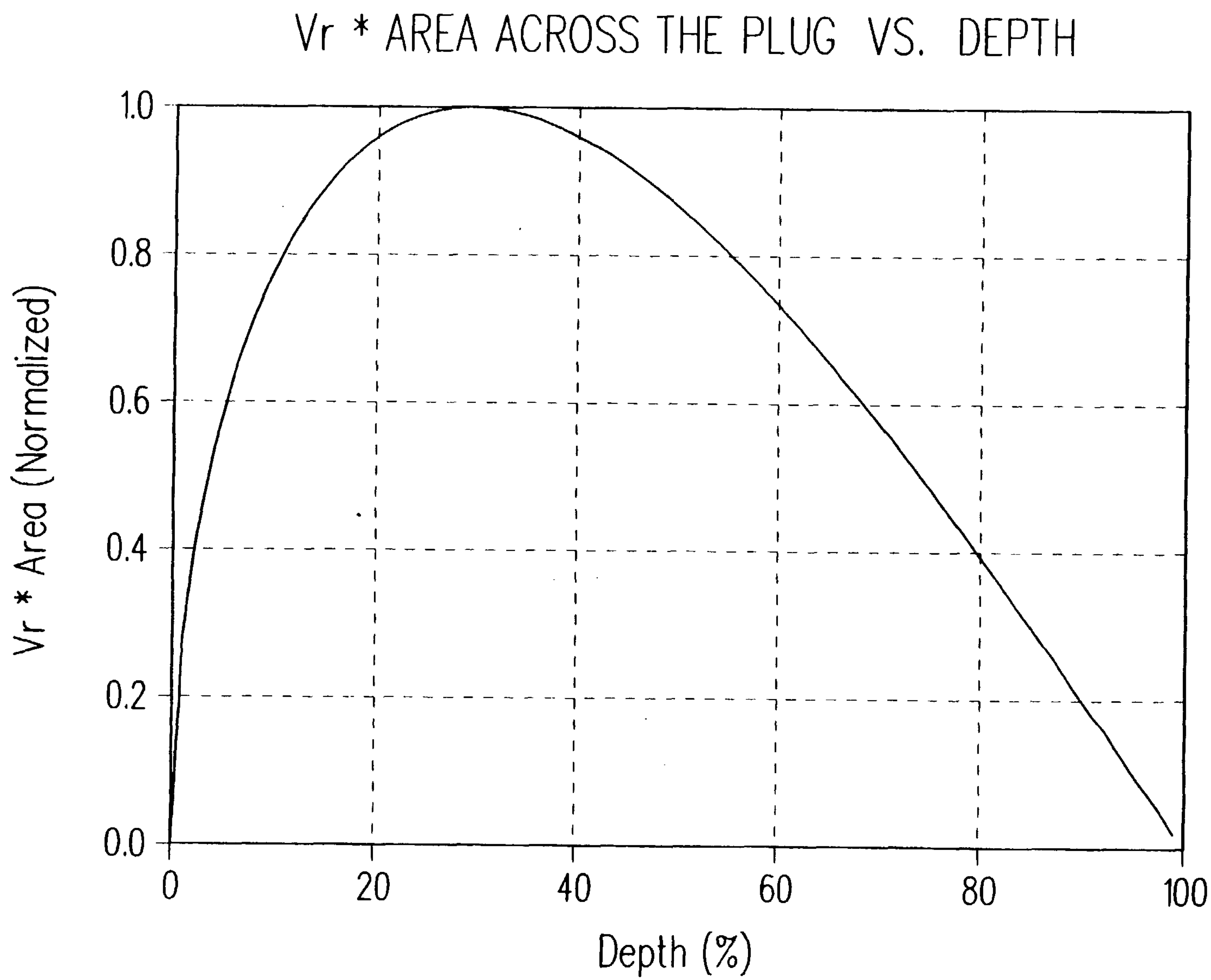
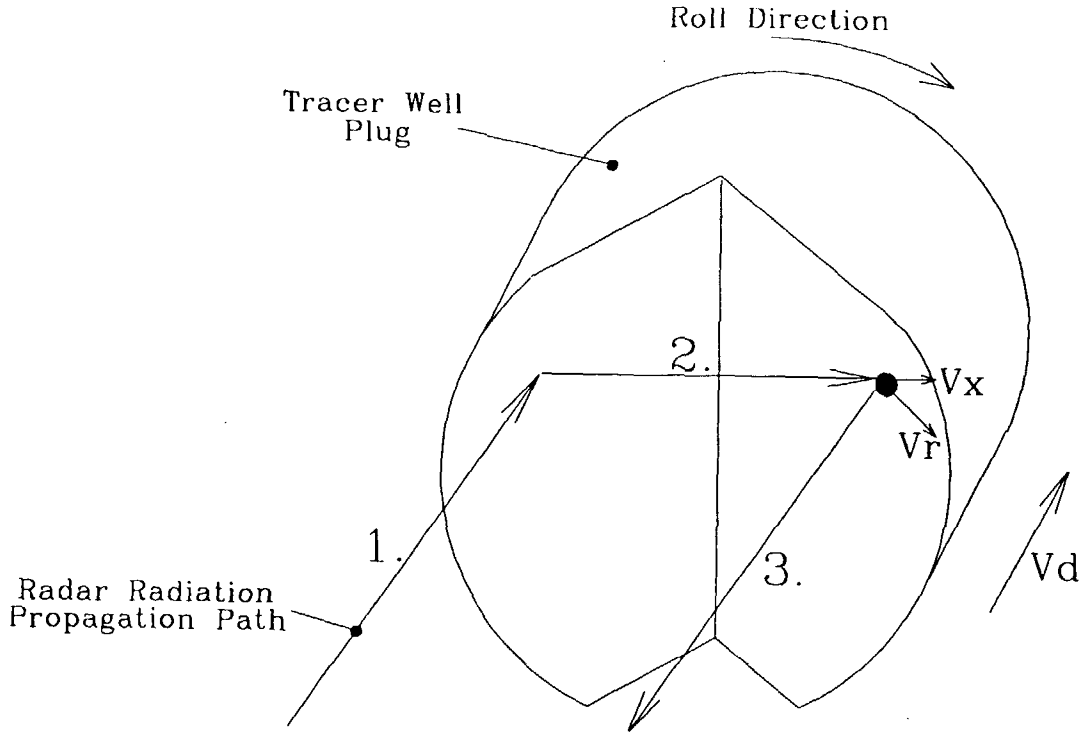


Figure 4. Depth When V_r and Area Across the Plug are Optimized.



1. Radiation hits plug and Doppler shift, f_{d1}, due to V_d is created.
2. Radiation is reflected to opposite side of plug where it "sees" the component, V_x, of the tangential velocity V_r, and Doppler shift, f_{d2} is created.
3. Radiation returns to radar with Doppler shifts caused by both V_d and V_r.

Figure 5. Radar Radiation Path During Contact With the Tracer-Well Plug.

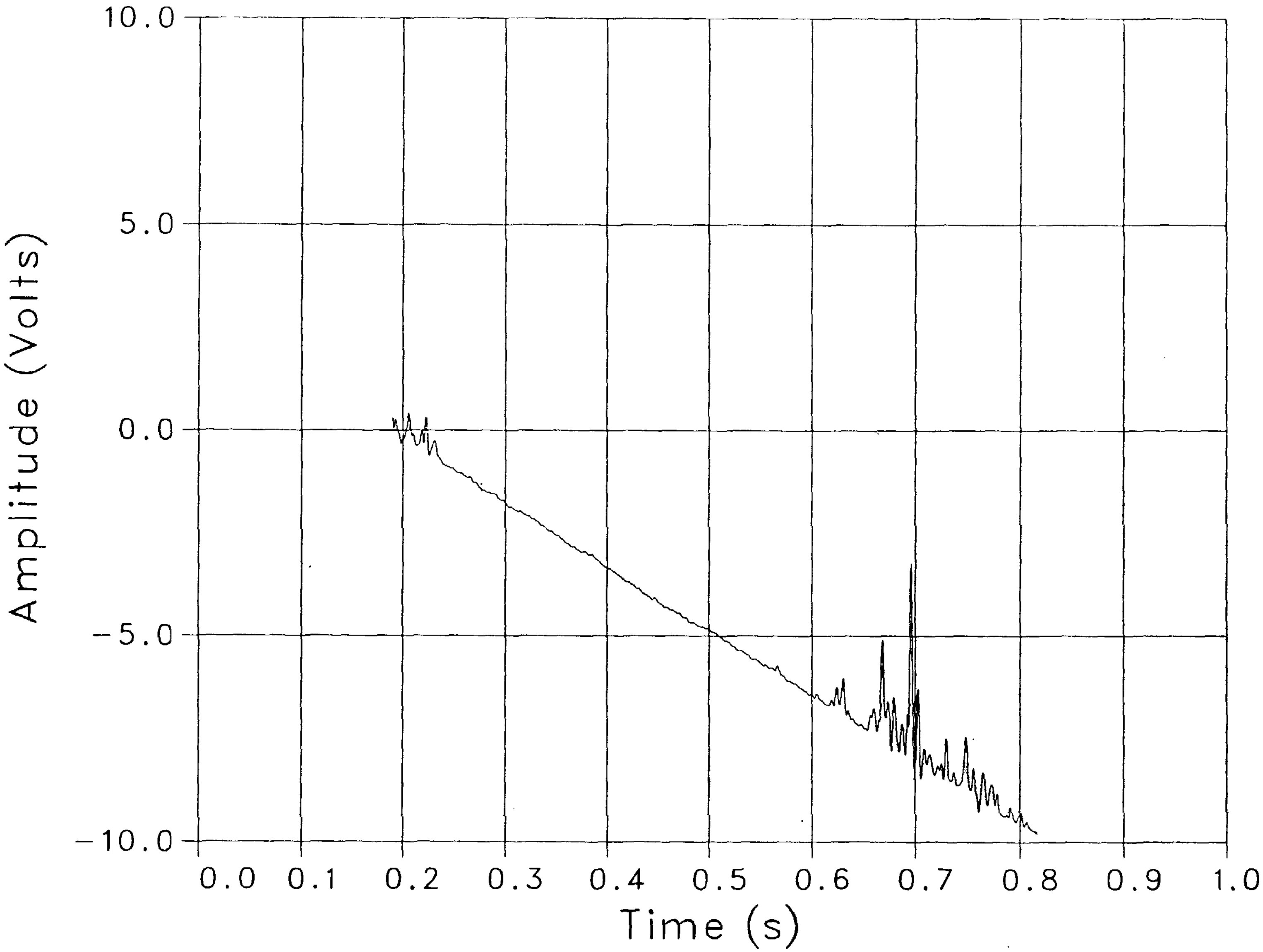


Figure 6. <u>Discriminated Doppler Radar Data From a Projectile Without the Tracer-Well Plug</u>.

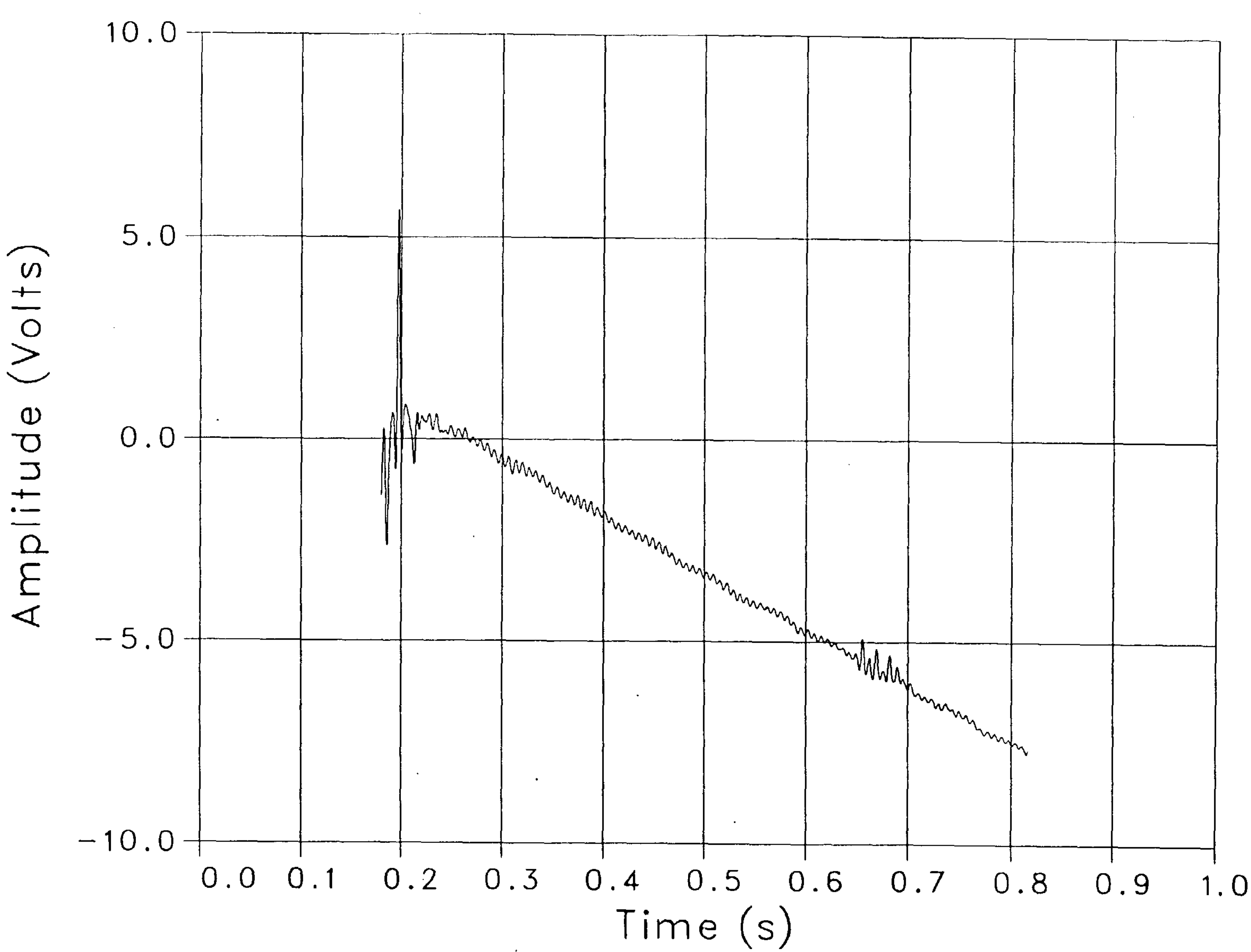


Figure 7. Discriminated Doppler Radar Data From a Projectile With the Tracer-Well Plug.

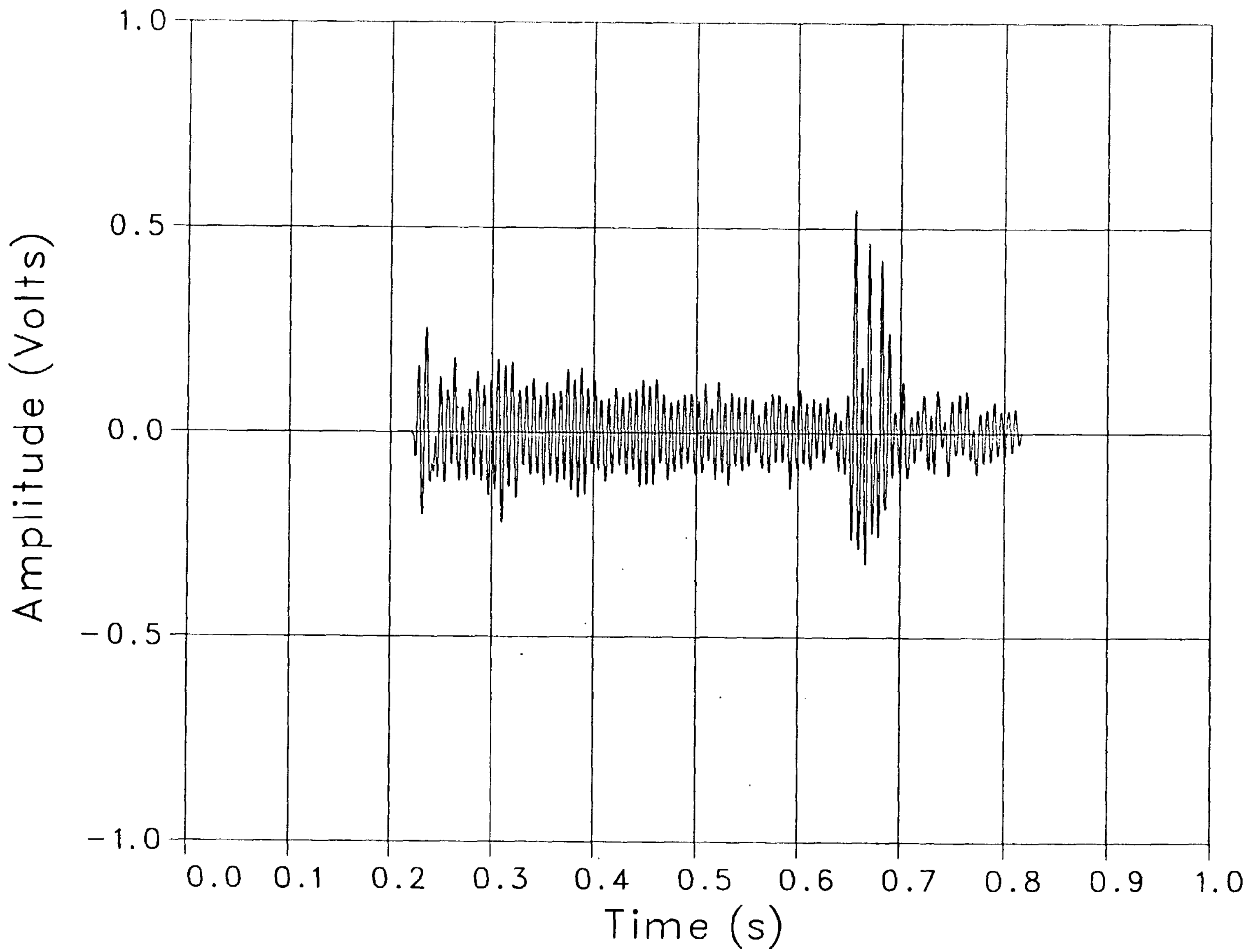


Figure 8. Band Pass Filtered, Discriminated Data of Projectile With the Tracer-Well Plug.

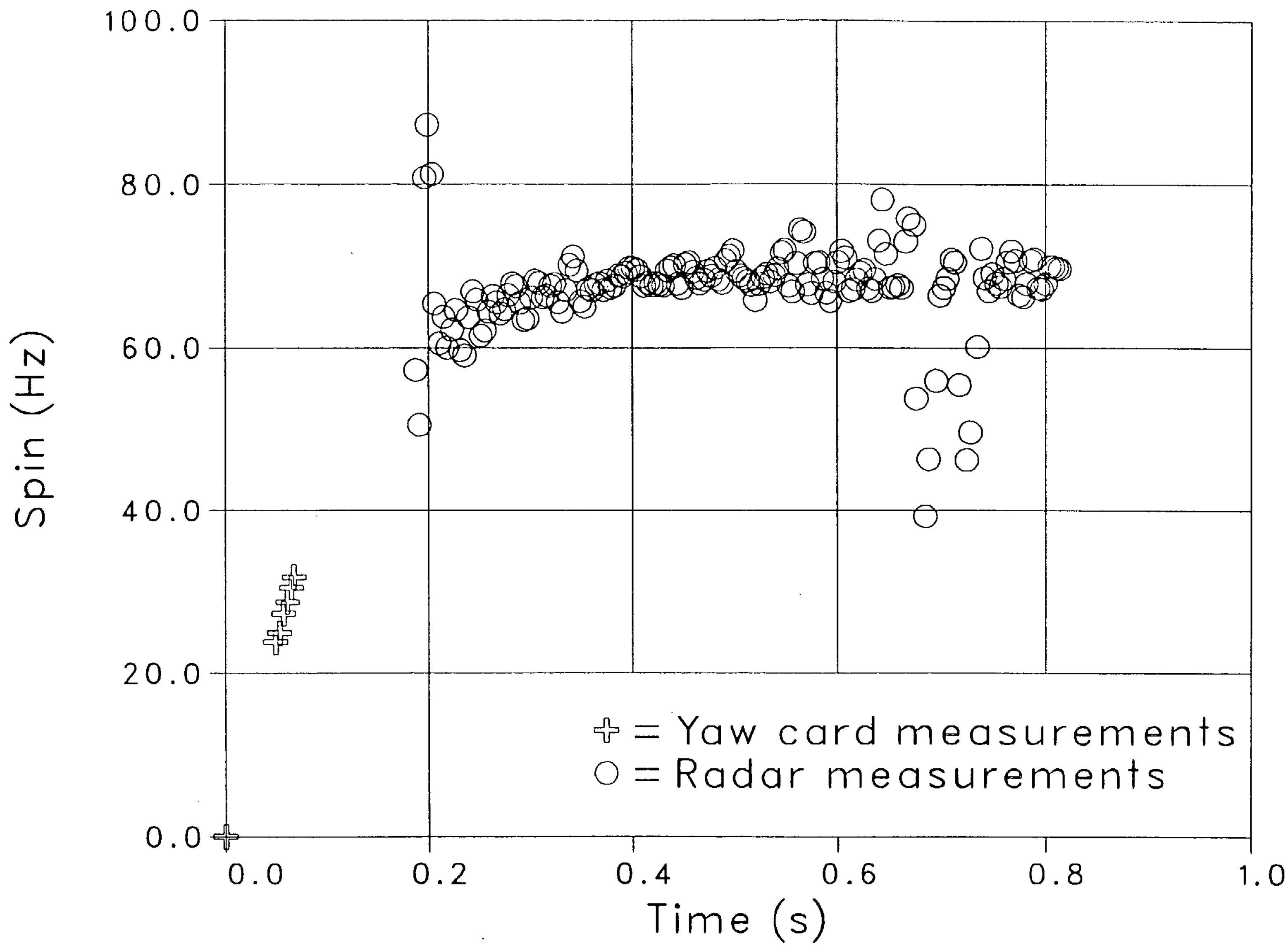


Figure 9. Spin History of Round P1.

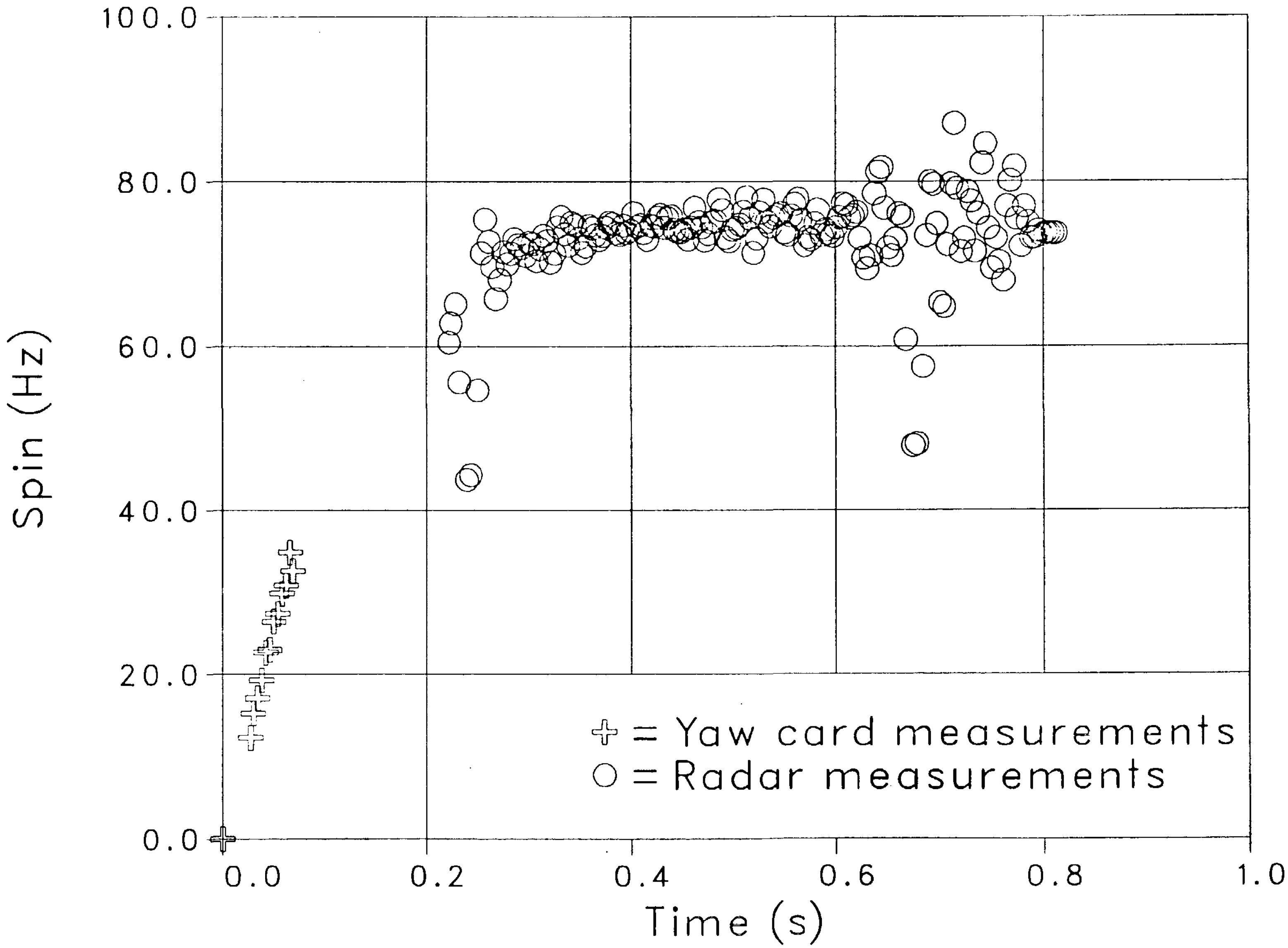


Figure 10. Spin History of Round P2.

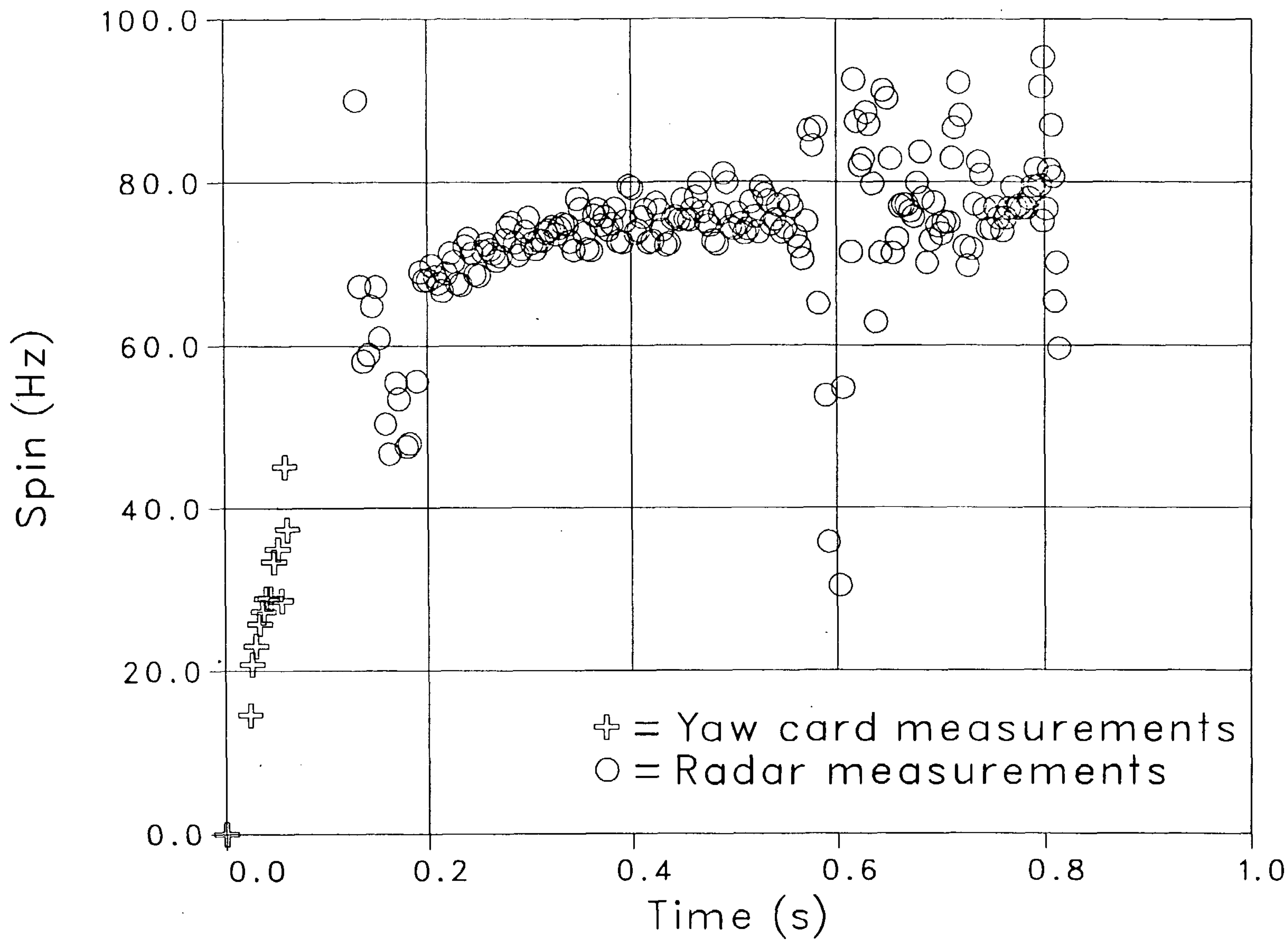


Figure 11. Spin History of Round P3.

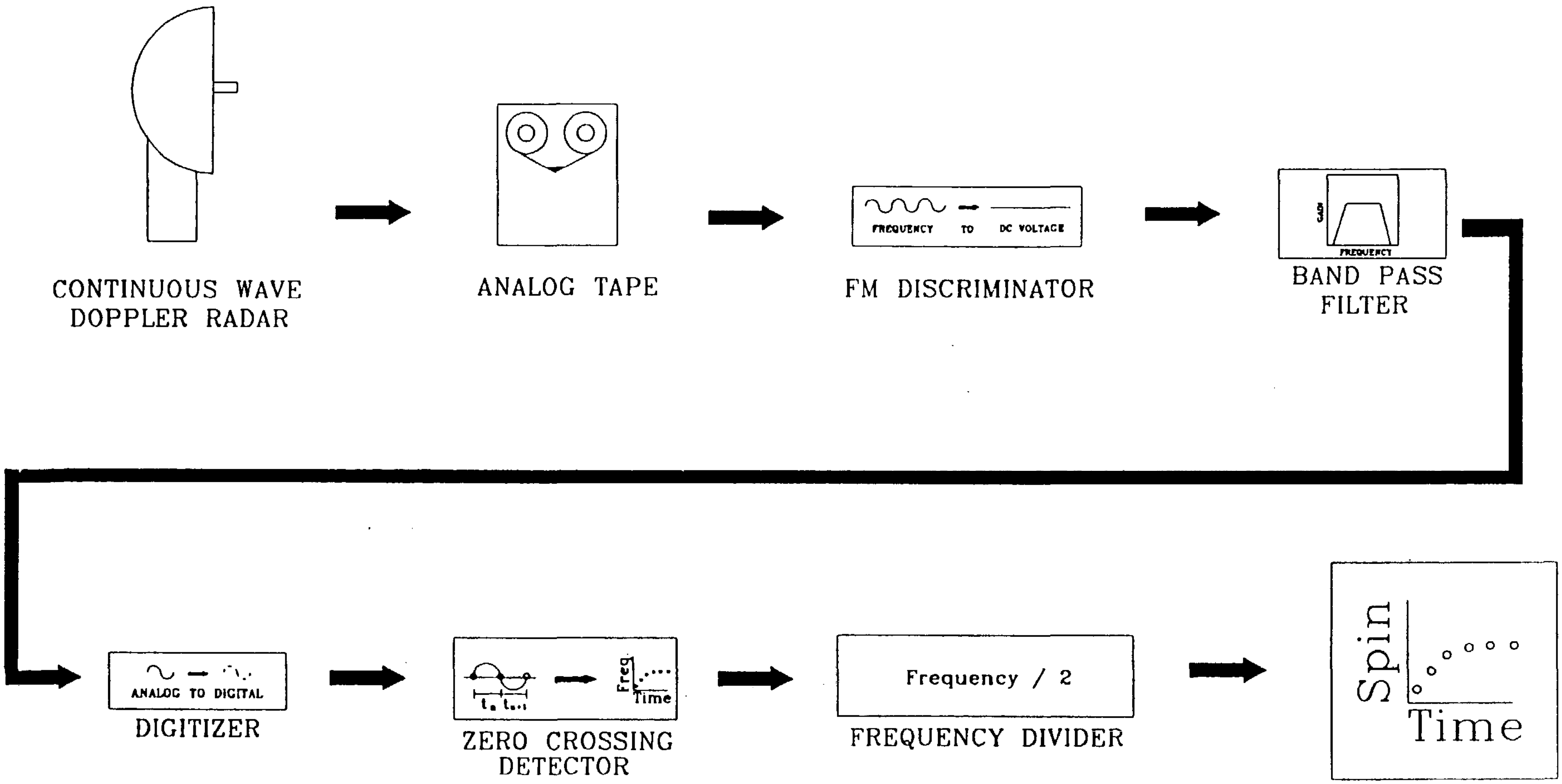


Figure 12. Equipment Used to Reduce the Doppler Data.

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